Study of rotating quark-gluon plasma within lattice simulation

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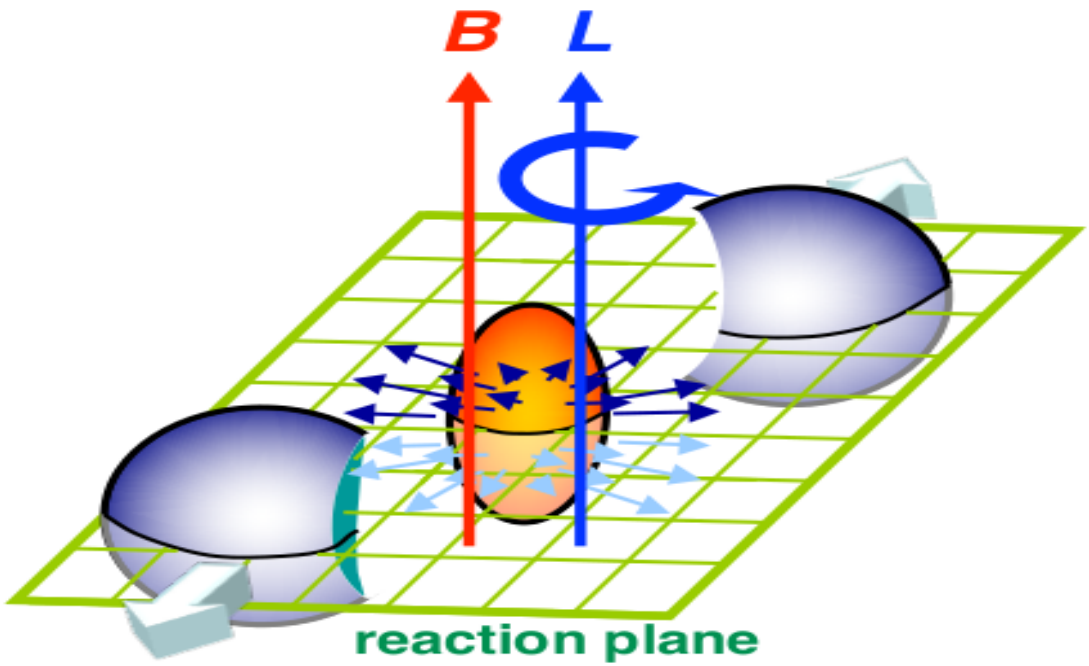
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Outline:

- Introduction
- Spatial confinement/deconfinement transition
- Equation of state and the moment of inertia
- Free energy of rotating static quark
- Spin potential
- Conclusion

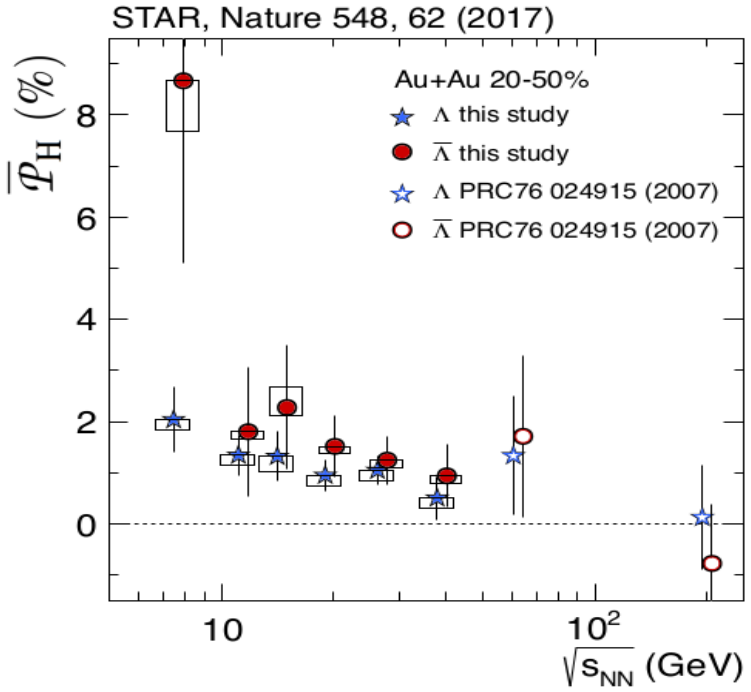
QCD under extreme conditions



- High temperature
- Intense magnetic field
- Large baryon density
- Huge acceleration
- Relativistic rotation

Rotation of QGP in heavy ion collisions





- Measurement of Λ, $\bar{\Lambda}$ polarization [STAR'17]
- $\Omega \sim 10$ MeV $(v \sim c$ at $r \sim 10 - 20$ fm, $\sim 10^{22}\, s^{-1})$
- The most vortical fluid ever observed!

How relativistic rotation influences QCD?

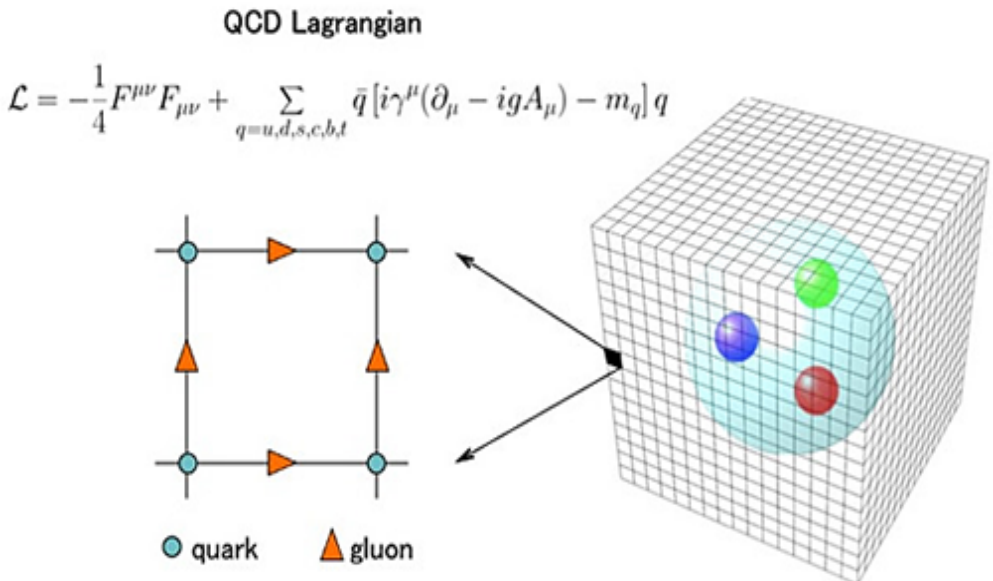
Quantum Chromodynamics(QCD)

- Degrees of freedom
  - Quarks q
  - Gluons A
- The QCD Lagrangian is well known

$$L = -\frac{1}{4}\sum_{a=1}^{8} F_a^{\mu\nu} F_{\mu\nu}^a + \sum_{f=u,d,s,\ldots} \bar{q}_f (i\gamma^\mu \partial_\mu - m) q_f + g \sum_{f=1}^{N_f} \bar{q}_f \gamma^\mu \hat{A}_\mu q_f$$

- Non-linear equations of motion with $g \sim 1$
- The main problem: calculation of observables based on the QCD Lagrangian
- Theoretical approaches contain assumptions with systematic errors which are difficult to estimate

Building lattice QCD



- Introduce regular cubic four dimensional lattice $N_s \times N_s \times N_s \times N_t = N_s^3 \times N_t$
- Lattice spacing–a
- Degrees of freedom
  - **Gluon fields:** 3x3 matrices $U \in SU(3)$, live on links
  - **Quarks fields:** column $q, \bar{q}$, live on sites

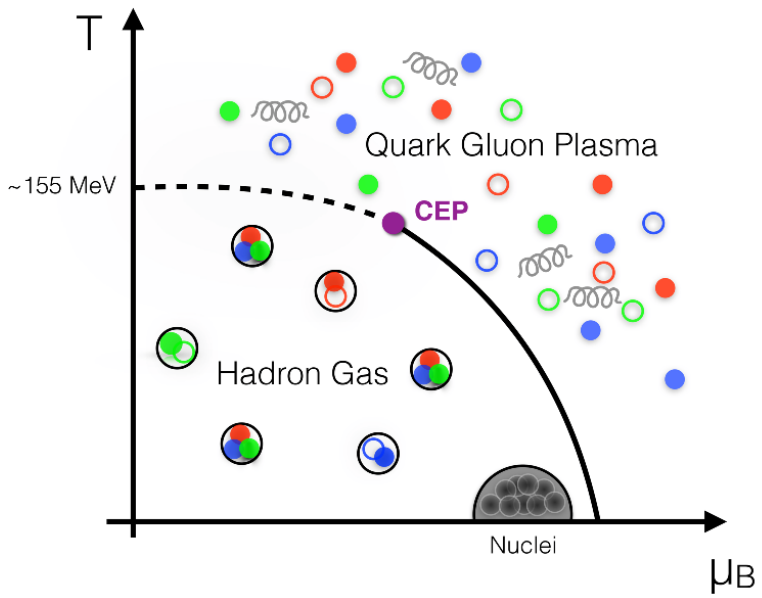
Lattice QCD

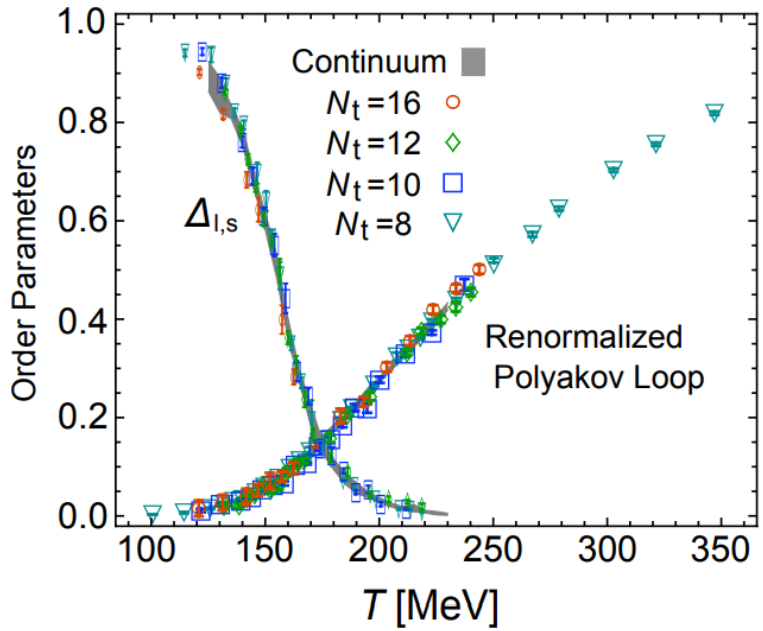
- QCD partition function (thermodynamic equilibrium!)

  $$Z = \int DU D\psi D\bar{\psi} \exp\left(-S_G - S_Q\right) = \int DU e^{-S_{eff}(U)}$$

- Hybrid Monte Carlo simulations
  (generation of gluon configurations with weight $\sim e^{-S_{eff}(U)}$)
- In continuum lattice partition function exactly reproduces QCD partition function
  - Gluon contribution: $S_G\big|_{a\to 0} = -\frac{1}{4}\sum_{a=1}^{8} F_a^{\mu\nu} F_{\mu\nu}^a$
  - Quark contribution: $S_Q\big|_{a\to 0} = \bar{q}(\gamma^\mu \partial_\mu + ig\gamma^\mu A_\mu + m)q$
- Carry out continuum extrapolation $a \to 0$
- Uncertainties (discretization and finite volume effects) can be systematically reduced
- The first principles based approach. No assumptions!
- Parameters: coupling constant $g(a)$ and masses of quarks $m_q(a)$

Phase transitions in QCD





- Confinement/deconfinement transtion

  Order parameter Polyakov line: P
  - Confinement: $P = 0$
  - Deconfinement: $P \neq 0$
- Chiral symmetry breaking/restoration transition

  Order parameter: chiral condensate $\langle \bar{\Psi}\Psi \rangle$
  - CS is broken: $\langle \bar{\Psi}\Psi \rangle \neq 0$
  - CS is restored: $\langle \bar{\Psi}\Psi \rangle = 0$

Rotating Gluodynamics/QCD

- The study is conducted in rotating reference frame (non-inertia frame)
- Influence of non-inertia reference frame can be reduced to external gravitational field
- The metric is well known $ds^2 = g_{\mu\nu} dx^\mu dx^\nu$

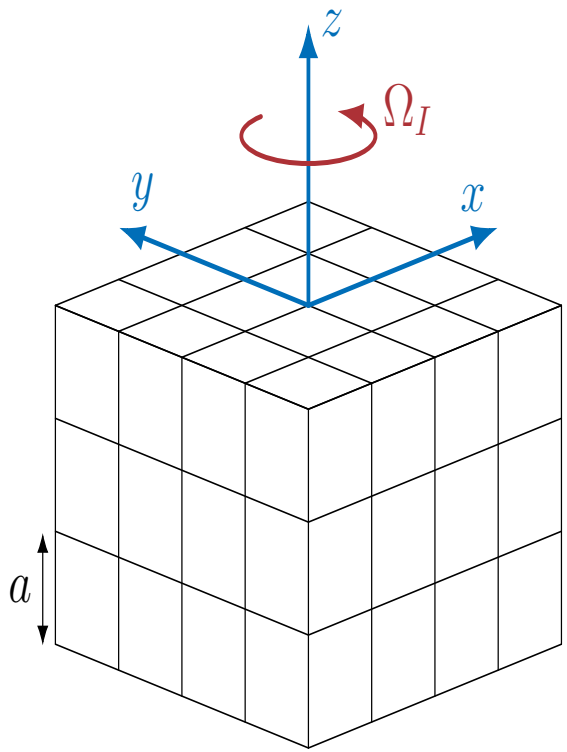
$$g_{\mu\nu} = \begin{pmatrix} 1 - r^2\Omega^2 & \Omega y & -\Omega x & 0 \\ \Omega y & -1 & 0 & 0 \\ -\Omega x & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}$$

- Aim: investigation of confinement/deconfinement phase transition in rotating gluodynamics/QCD

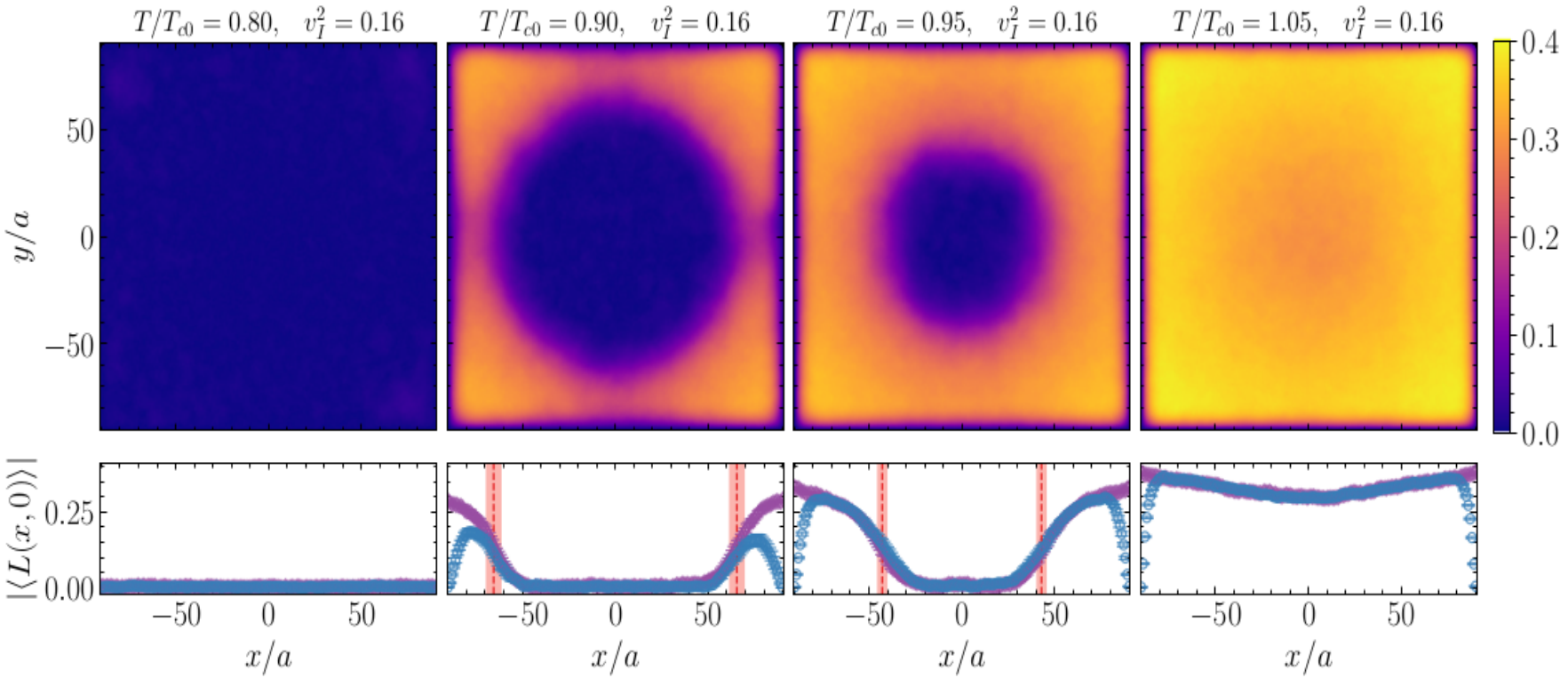
[V. Braguta'2024, V. Braguta'2025]

Lattice setup

- Partition function
  $Z = \int DAe^{-S}$,
  $S = \frac{1}{4g^2} \int d^4x \sqrt{g}\ g^{\mu\nu} g^{\alpha\beta} F_{\mu\alpha} F_{\nu\beta}$
- Focus on confinement/deconfinement transition
  Measure local Polyakov loop $L(\vec{r})$
- Small angular velocities:
  $\Omega \ll \Lambda_{QCD}$ and $\Omega R < 1$
- Open/Dirichle/Periodic BCs
  Don't see significant dependence on the BCs
- The sign problem for $\Omega \neq 0$
  simulations are conducted at $\Omega_I = i\Omega$
- We use the designation: $v_I = \Omega R$

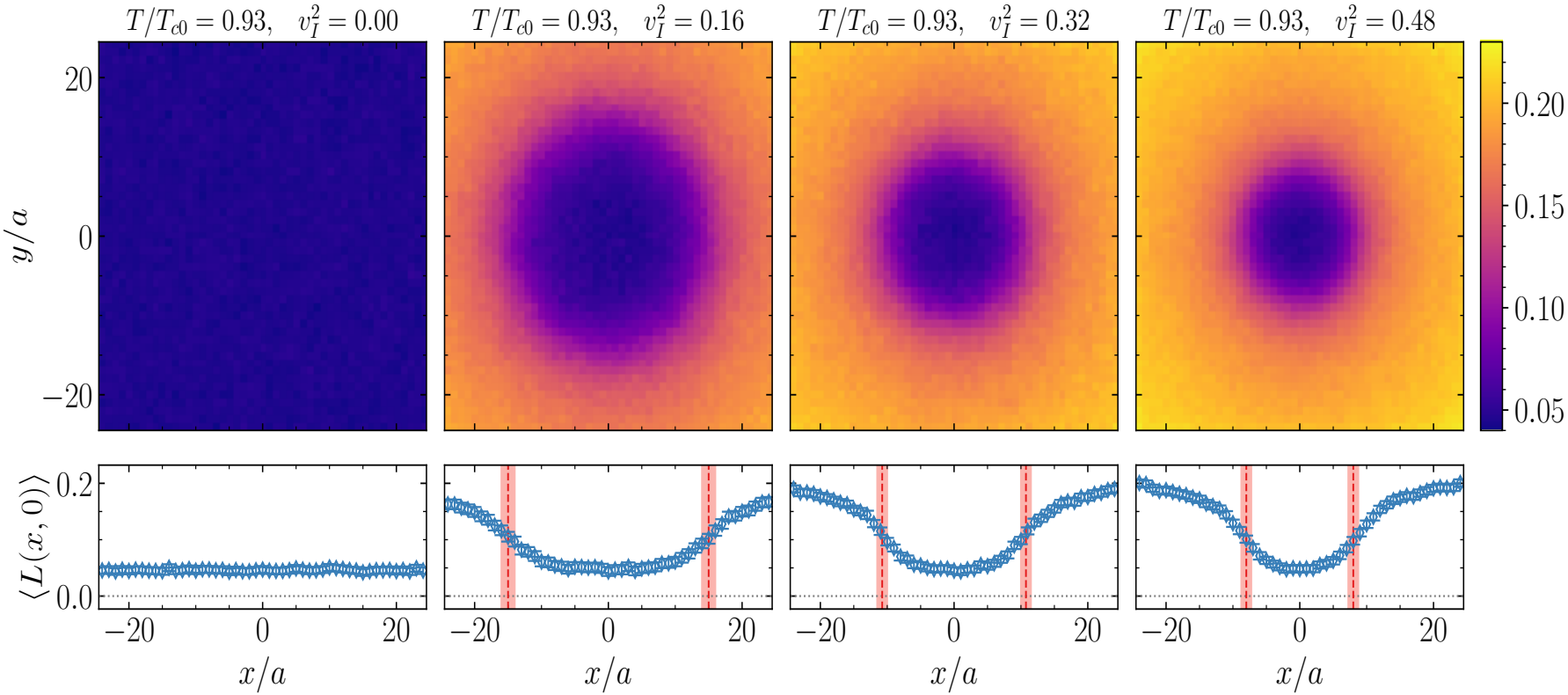


Spatial phase transition in rotating GP



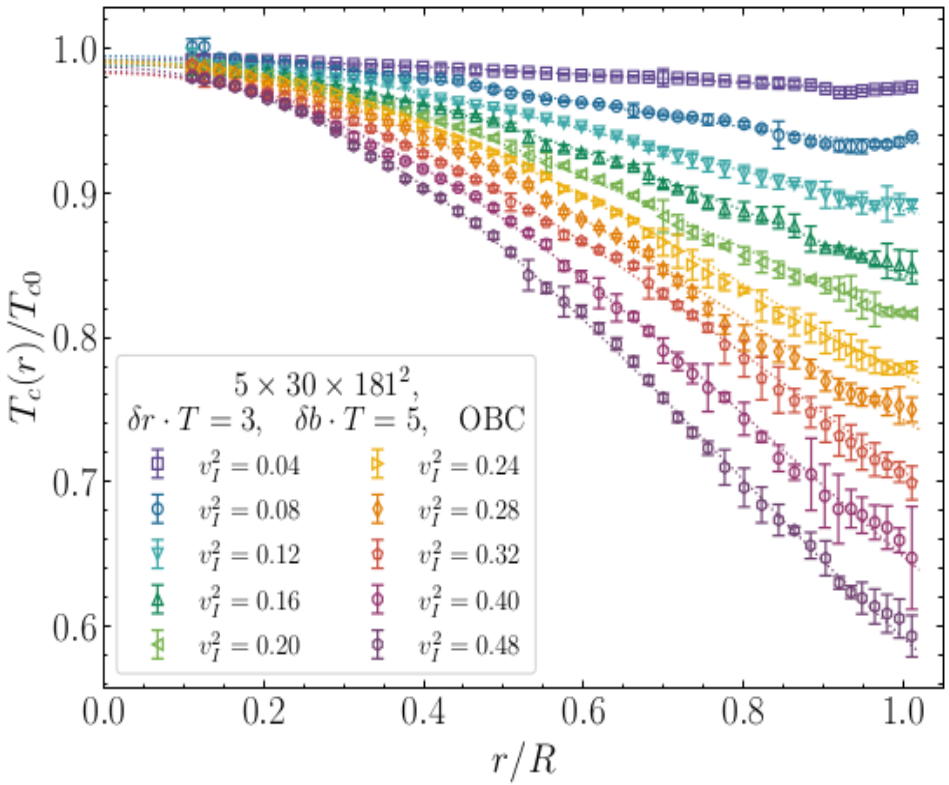
- Finite temperature confinement/deconfinement becomes spatial transition:
  For a certain parameters spatially separated confinement and deconfinement phases coexist simultaneously
- For $\Omega^2 < 0$ confinement in the center and deconfinement in the periphery
- Confinement/inhomogeneous state/deconfinement
  Inhomogeneous state takes place below T_{c0}

Spatial transition in QCD



- It remains to be true for quarks (Preliminary results!)

Local critical temperature $T_c(r, \Omega_I)$

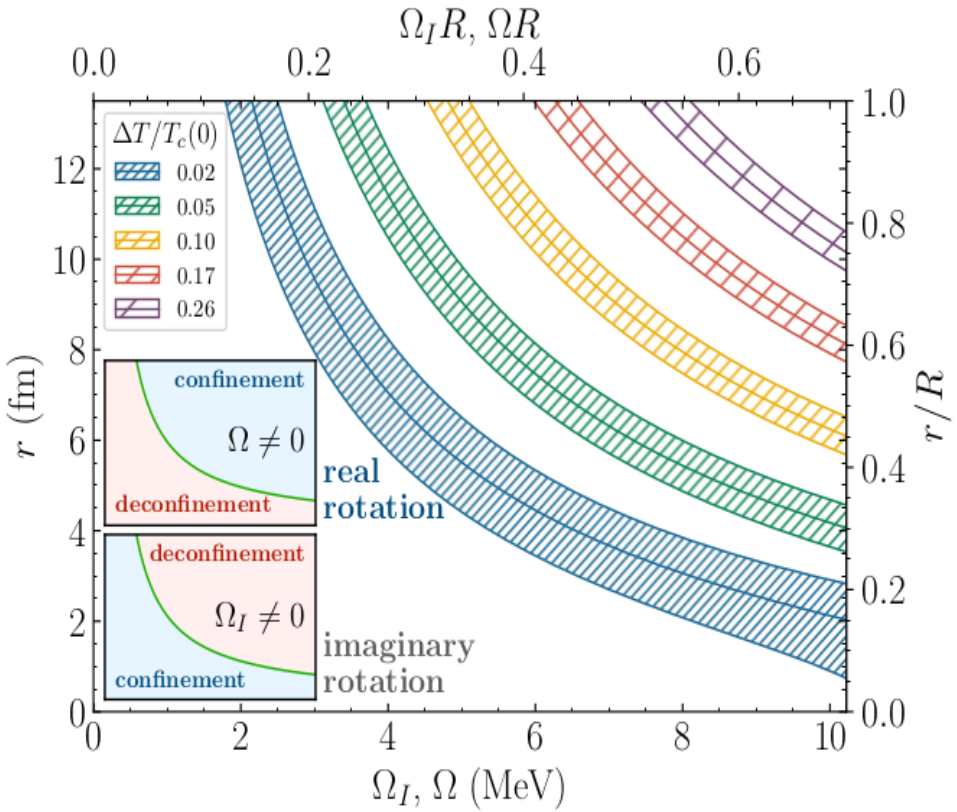


- Our results can be well described by the formula

$$\frac{T_c(r,\Omega_I)}{T_{c0}} = 1 - \kappa_2(\Omega_I r)^2, \quad \kappa_2 > 0$$

- Within the uncertainty $\frac{T_c(r=0,\Omega_I)}{T_{c0}} = 1$
- Weak dependence on the simulation parameters

Analytical continuation to real rotation



- Analytical continuation $\Omega_I^2 \to -\Omega^2$:

$$\frac{T_c(r,\Omega)}{T_{c0}} = 1 + \kappa_2 (\Omega r)^2$$

- Inhomogeneous state can be realised for $T > T_{c0}$
- Deconfinement in the center and confinement in the periphery

Local action

$$S_G = \int d^4x \left[\frac{1}{2g^2} \left((E_x^a)^2 + (E_y^a)^2 + (E_z^a)^2 + (H_y^a)^2 \right) + \right.$$
$$\left. + \frac{1}{2\tilde{g}^2} \left((H_x^a)^2 + (H_z^a)^2 \right) \right]$$

- Linear in Ω terms can be neglected
- External gravitational field leads to the asymmetric action with $\frac{g^2}{\tilde{g}^2} = 1 - (\Omega r_0)^2$
- The asymmetry $g^2/\tilde{g}^2$ is larger in the periphery region leading to the shift of the local critical temperature
- Local thermalization approximation was checked on the lattice

EoS of rotating plasma

- Free energy of rotating QGP

  $F(T,R,\Omega) = F_0(T,R) - \frac{F_2}{2}\Omega^2 - \frac{F_4}{4}\Omega^4 + ...$

- Total momentum

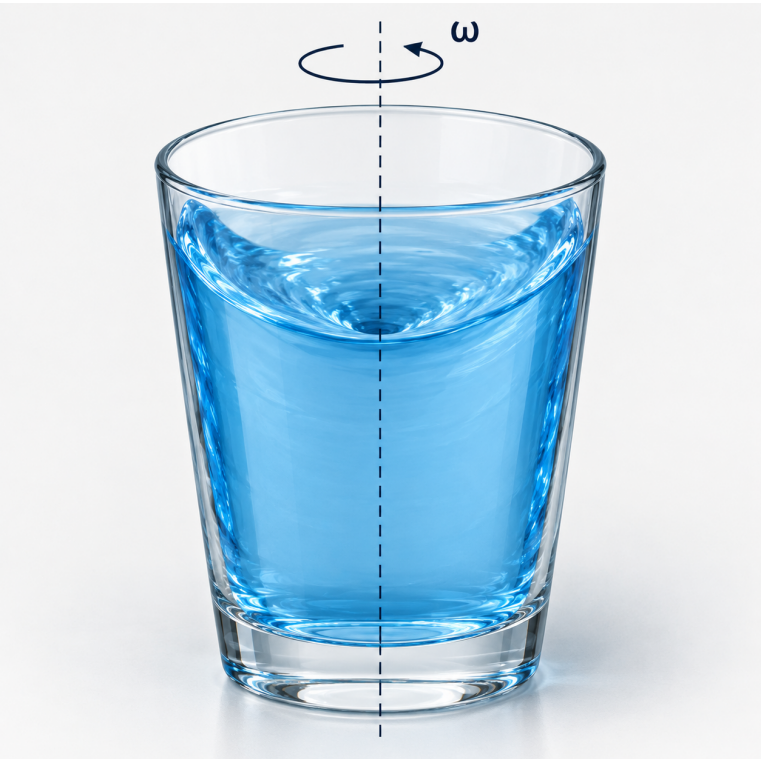
  $$J_z = -\left(\frac{\partial F}{\partial \Omega}\right)_T = (F_2 + F_4\Omega^2)\cdot\Omega$$

- Moment of inertia

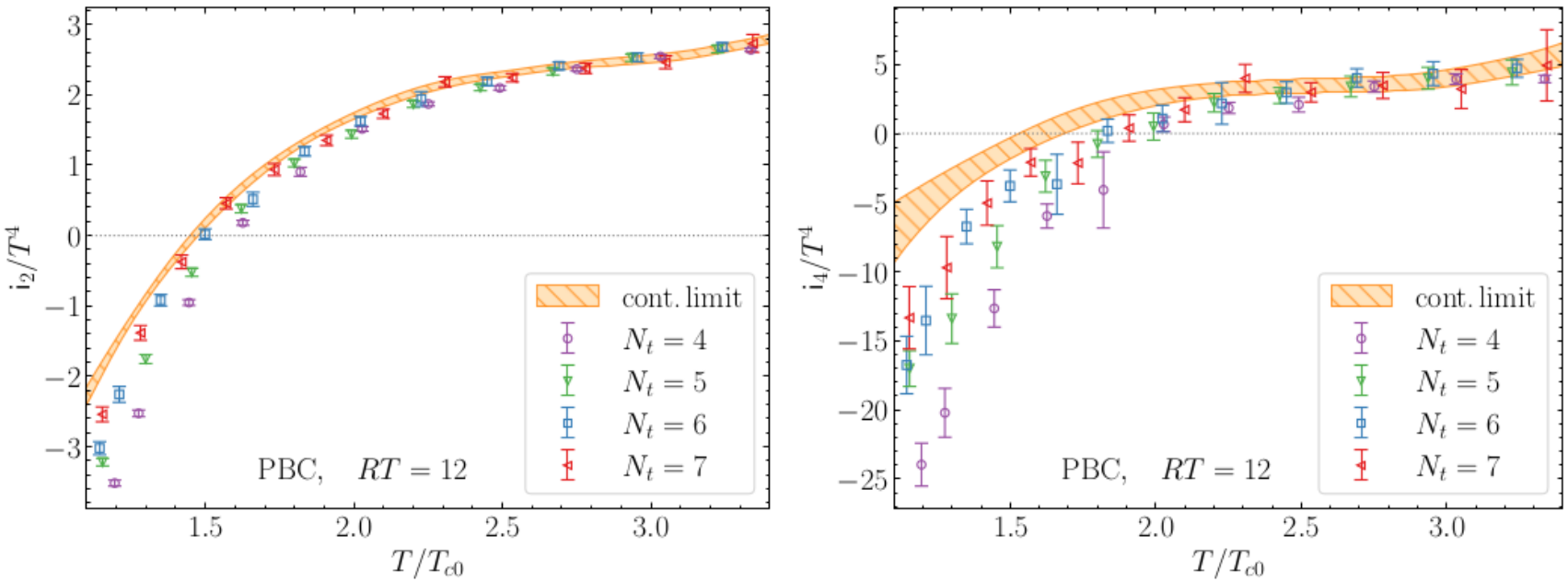
  $$I = \frac{J_z}{\Omega} = (F_2 + F_4\Omega^2)$$

- F_2–moment of inertia at vanishing Ω
  F_4–deformation due to rotation, $F_4 > 0$

- We calculate: $i_2 = \frac{F_2}{VR^2}, \quad i_4 = \frac{F_4}{VR^4}$



Moment of inertia of gluon plasma

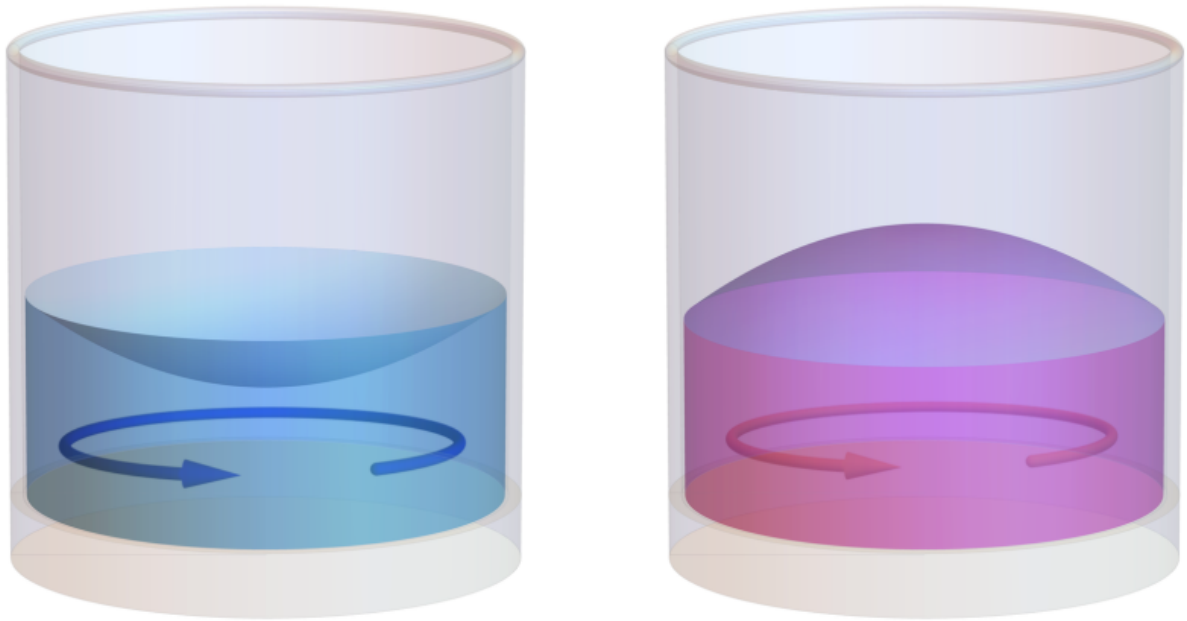


- EoS of gluon plasma

  V. Braguta et al., JETP Lett. 117 (2023) 9; 639-644, Phys.Lett.B 852 (2024) 138604; Phys.Part.Nucl. 57 (2026) 1146; to be published

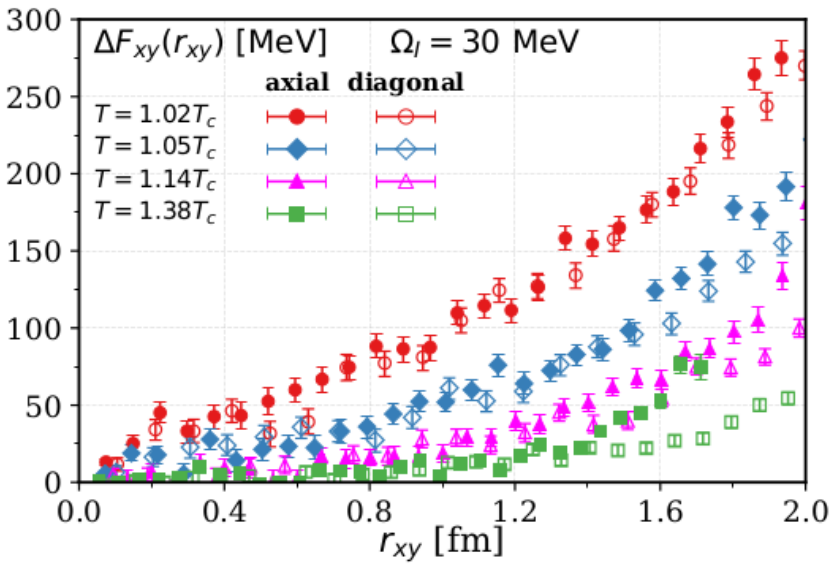
- $i_2 < 0$ for $T < 1.5T_c$ and $i_2 > 0$ for $T > 1.5T_c$
- $i_2 < 0$ is related to magnetic condensate and the scale anomaly

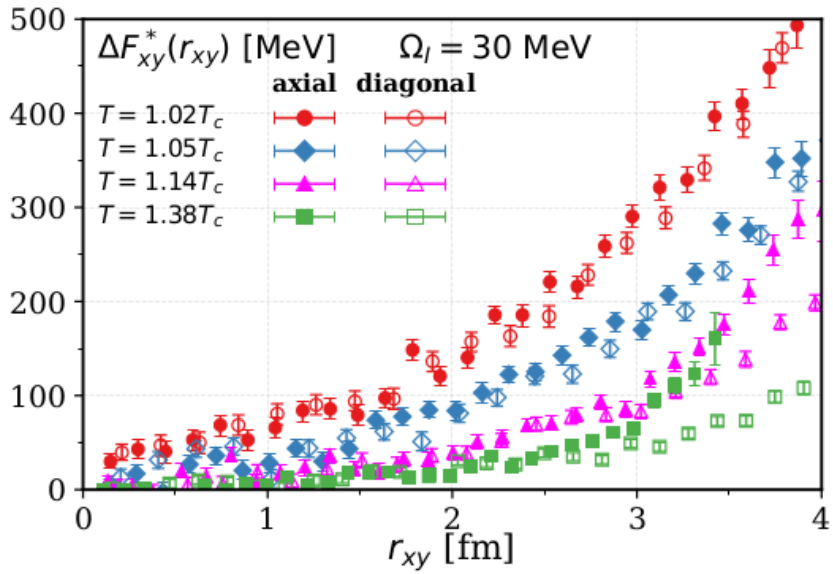
Moment of inertia of gluon plasma



- $i_4 < 0$ for $T < (1.6 - 1.8) \cdot T_c$ and $i_4 > 0$ for $T > (1.6 - 1.8) \cdot T_c$
- For $(\Omega R)^2 \sim 1/3, \quad \delta I / I_0 \sim 80\%$

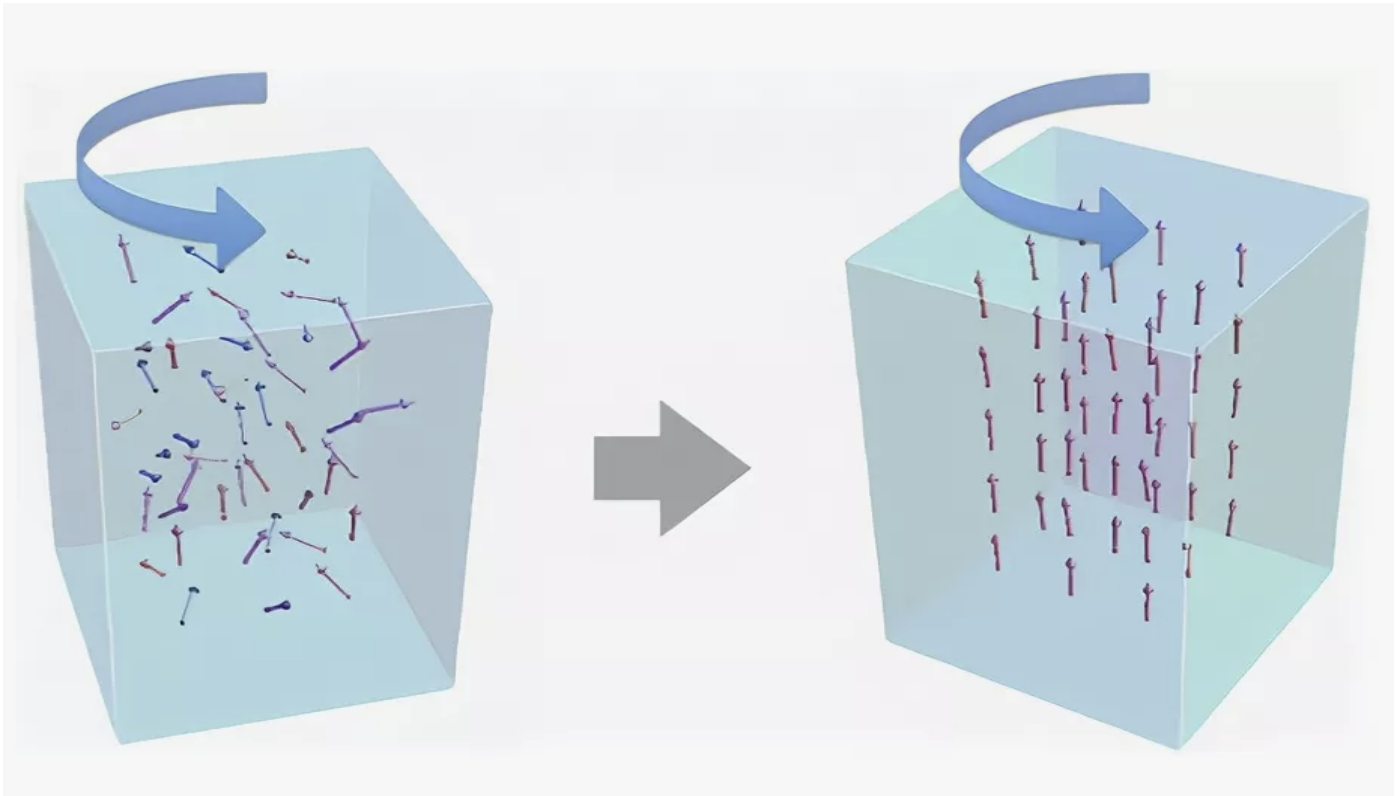
Free energy of rotating static quark





- Interaction potential of rotating static quarks
  Heng-Tong Ding et al., e-Print: 2607.26939
- $\Delta F = a\Omega^2 + b(\Omega r)^2$, $b > 0$ $\Rightarrow$ centripetal force acts on static quark
- For usual rotation $\Delta F = b(\Omega r)^2$, $b < 0$ $\Rightarrow$ centrifugal force
- This phenomenon takes place in the region $T \sim T_c$

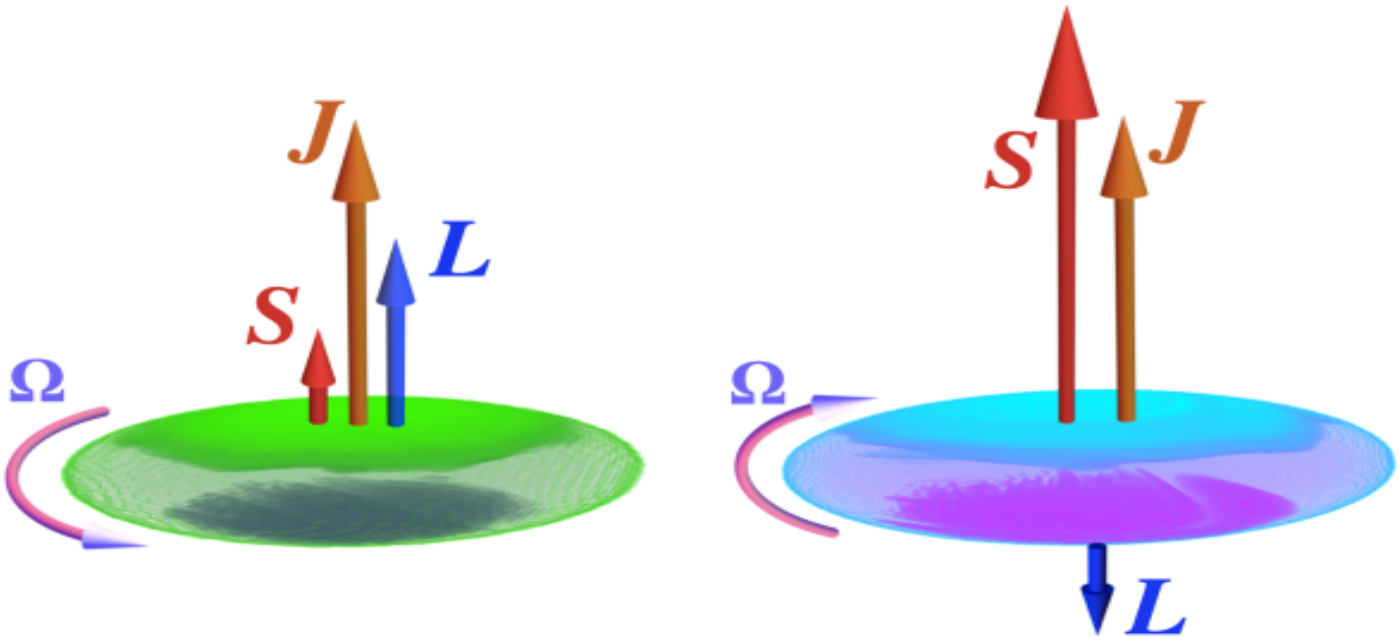
Barnett effect



- Rotation polarizes spins of ferromagnetic

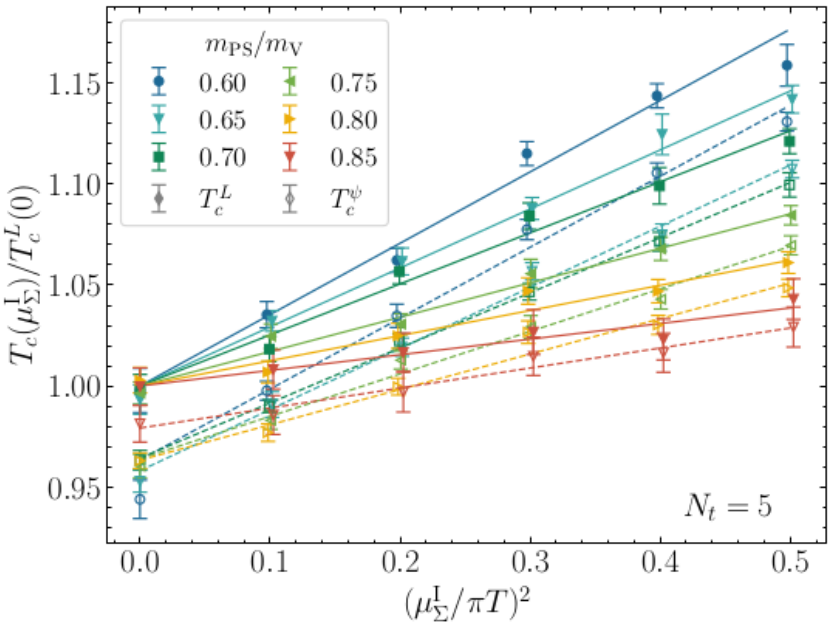
the picture from *doi: 10.3389/fphy.2015.00054*

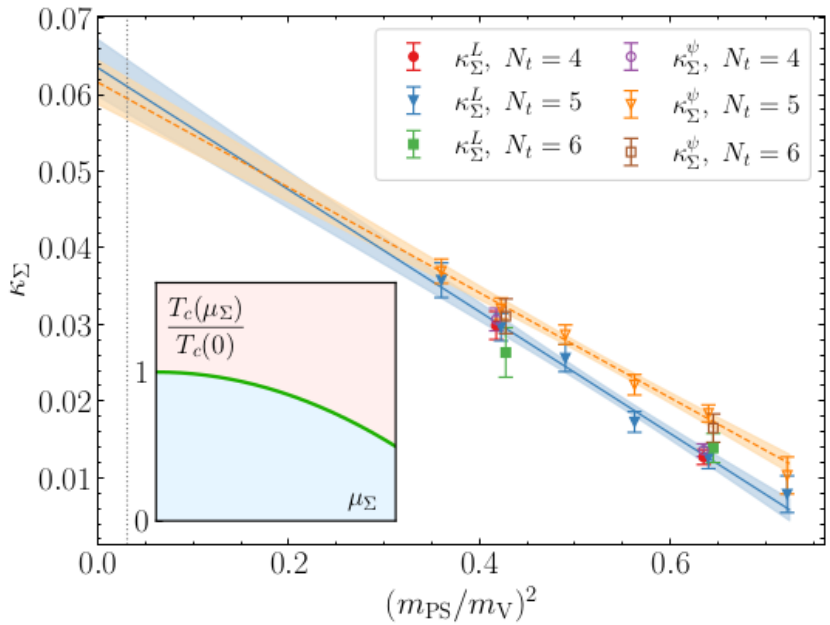
Negative Barnett effect



- $\vec{J} = I_0 \vec{\Omega} = -\left(\frac{\partial F}{\partial \vec{\Omega}}\right)_T, \quad \vec{J} = \vec{L} + \vec{S}$
- For classical motion $\vec{J} = \vec{L}$ and $I_0 > 0$
- But the spin $\vec{S}$ is quantum
- The term $\langle H^2 \rangle$ is related to spin of gluons
- $\vec{L} \uparrow\uparrow \vec{\Omega}, \quad \vec{S} \uparrow\downarrow \vec{\Omega}$ might lead to $\vec{J} \uparrow\downarrow \vec{\Omega}$ and $I_0 < 0$

QCD at finite spin density





- Spin potential μ_Σ: $Z = Tr[e^{-\beta \hat{H}}] \to Tr[e^{-\beta(\hat{H} - \mu_\Sigma \hat{S})}]$
- Lattice simulation at imaginary μ_Σ

  V. Braguta et al., Phys.Rev.D 111 (2025) 11, 114508
- Spin density decreases the critical temperatures

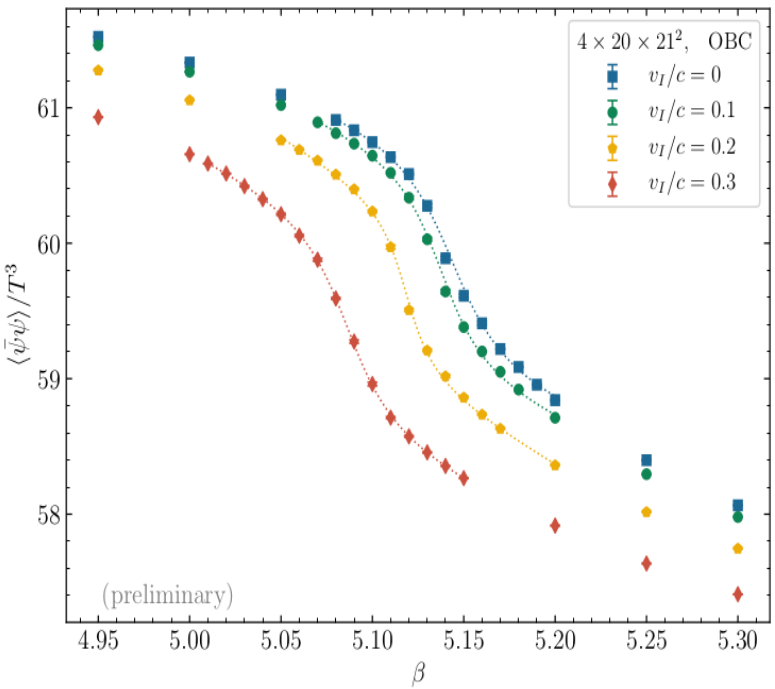
$$\frac{T_c(\mu_\Sigma)}{T_c} = 1 - \kappa_\Sigma \mu_\Sigma^2, \quad \kappa_\Sigma > 0$$

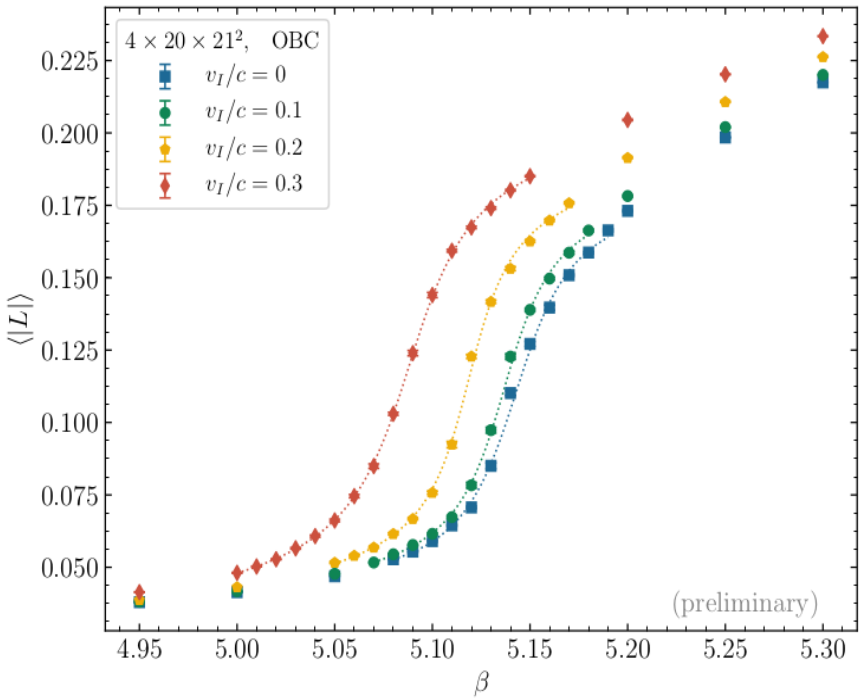
Conclusion

- Lattice studies of rotating gluodynamics and QCD have been reviewed
  - Equation of state and the moment of inertia
  - Spatial confinement/deconfinement transition
  - Free energy of rotating static quark
  - Spin potential
- One observes unusual phenomena in the region $T \sim T_c$: Negative moment of inertia, spatial deconfinement transition, centripetal force for rotating static quark
- These phenomena disappear at larger temperatures and might be related to behaviour of spin in QCD

THANK YOU!

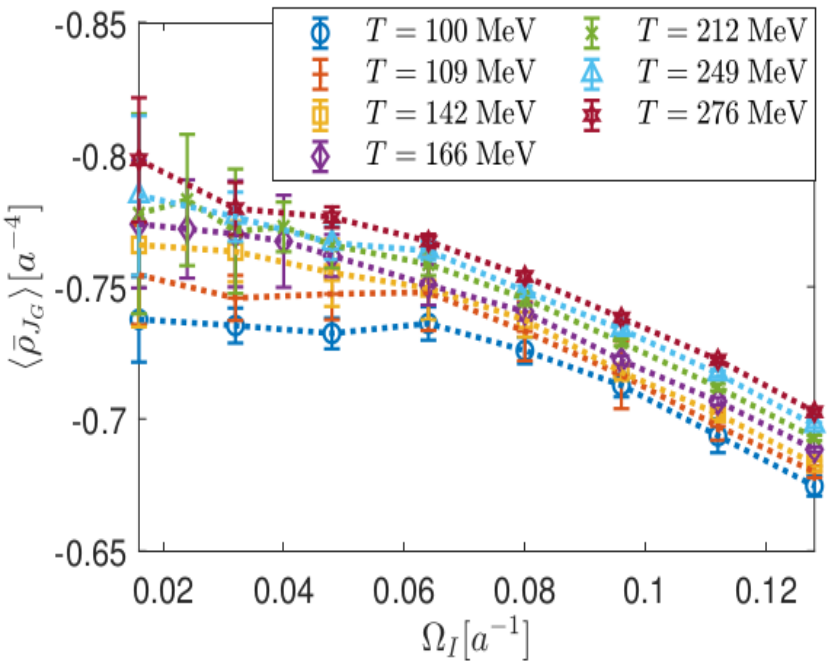
Backup slides: Simulation with fermions

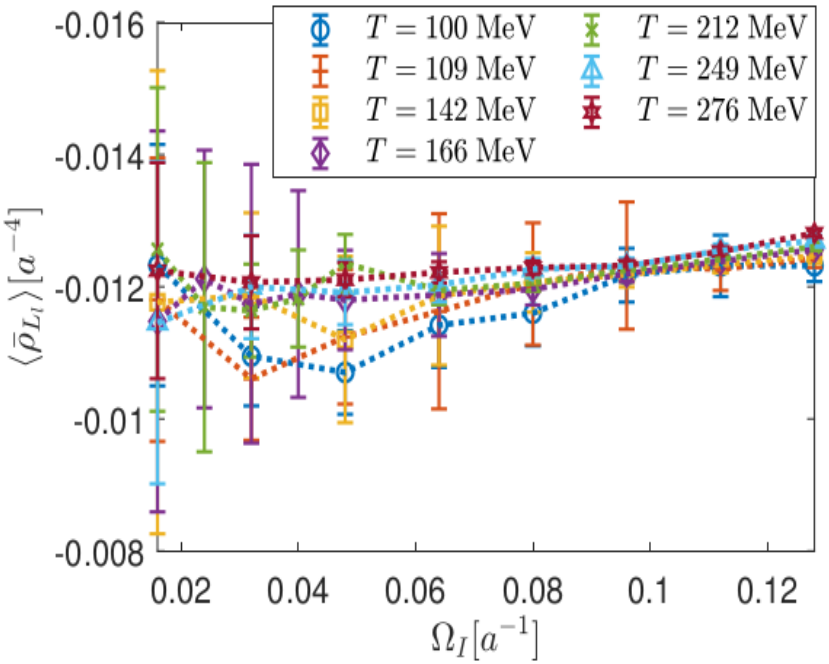




- Lattice simulation with Wilson fermions
- Critical couplings of both transitions coincide
- Critical temperatures are increased

Backup slides:
Simulation with fermions (e-Print: 2307.05755)





- Rotational rigidities: $\rho_{J_G} = \frac{J_G}{\Omega R^2}, \quad \rho_{L_f} = \frac{L_f}{\Omega R^2}$
- Spin susceptibility: $\zeta_f = \frac{s}{\Omega}$
- Negative moment of inertia